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G1G

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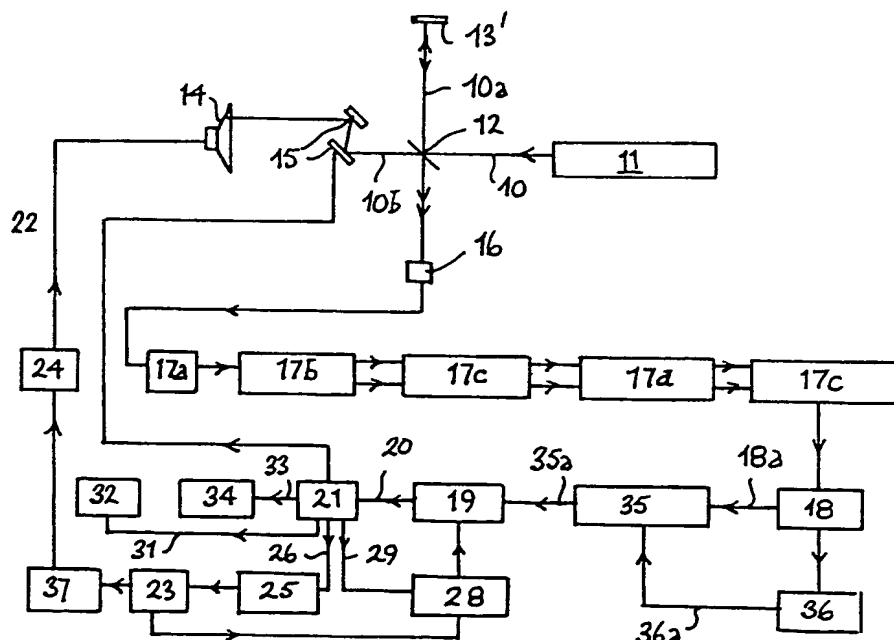
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(54) Doppler vibration measurement

(57) To measure the velocity gradients over a vibrating surface using Doppler shifts in a beam of radiation 10b reflected from the surface but without the need for a beam frequency shifting mechanism, a part 10a of the beam 10 unaffected by the motion of the vibrating surface is combined with the surface-reflected beam 10b to form a composite beam on which a beat frequency at the surface vibration frequency is imposed, which impinges on square-law sensor 16 to produce a component at twice the vibration frequency but in which information about the sign of the beat signal is lost. In order to recover this signal of the composite beam which correspond to a negative Doppler shift are distinguished from those which correspond to a positive Doppler shift either by some naturally-occurring difference such as magnitude or by an artificial "tagging" of one set of such half cycles.



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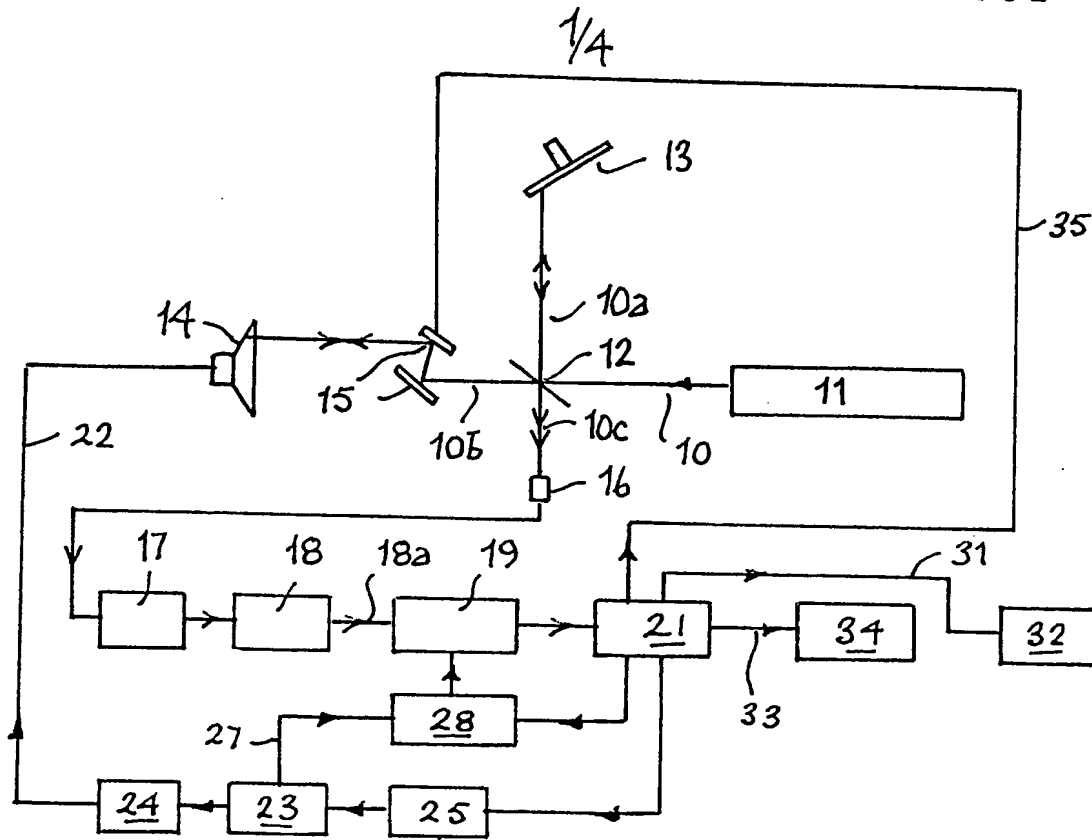


FIG. 1
[PRIOR ART]

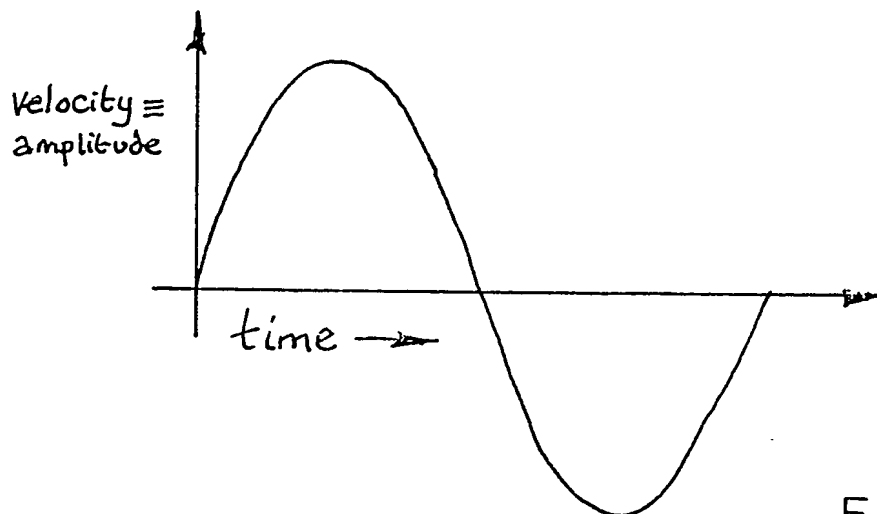


FIG. 2

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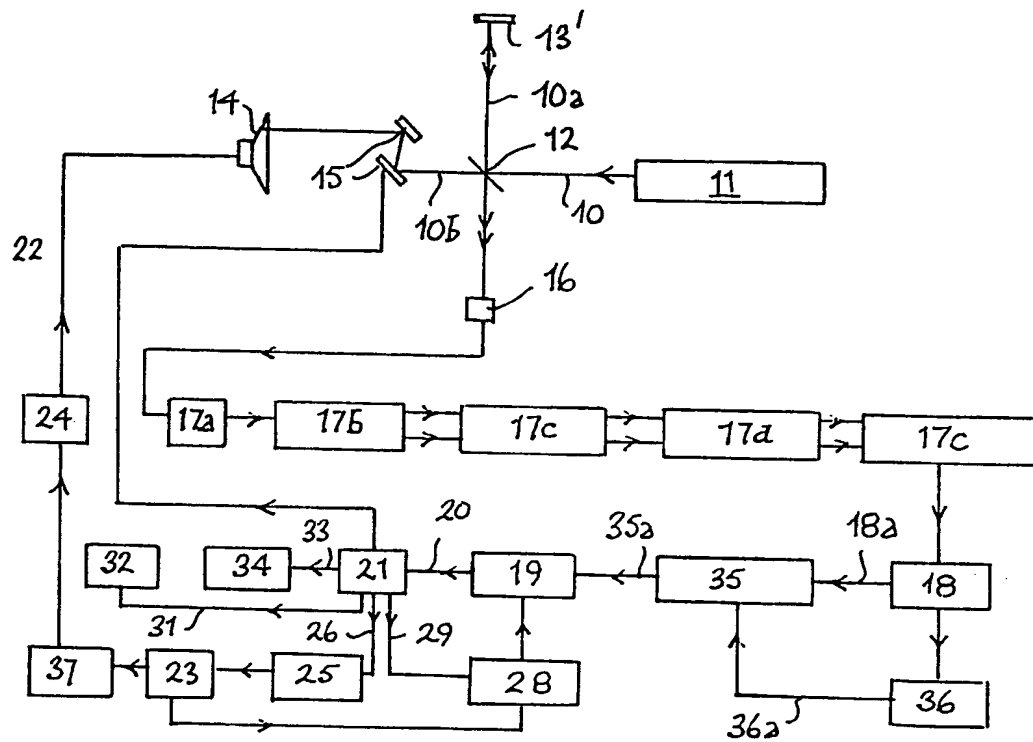


FIG. 3

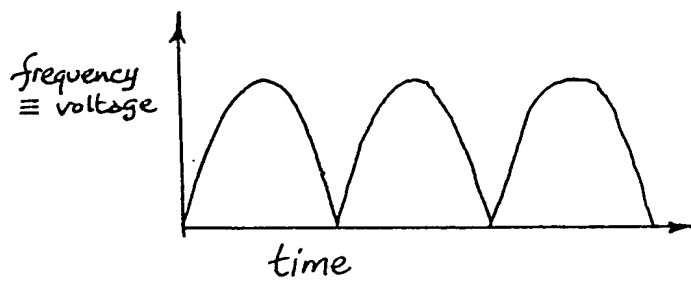


FIG. 4

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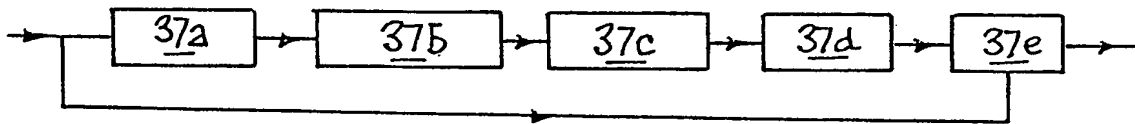


FIG. 5

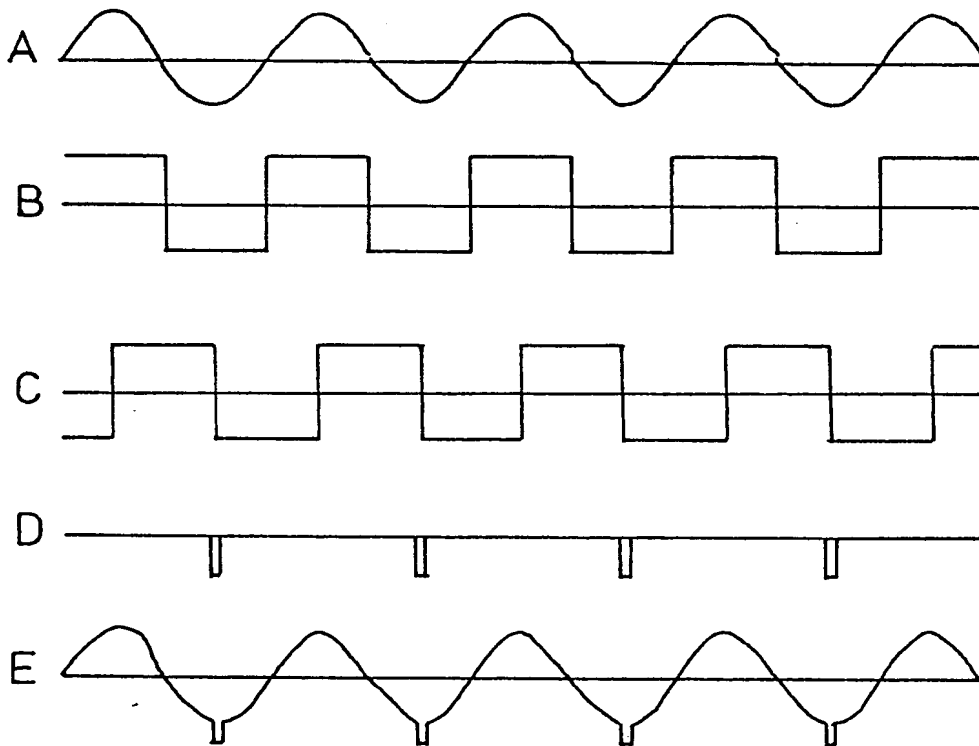
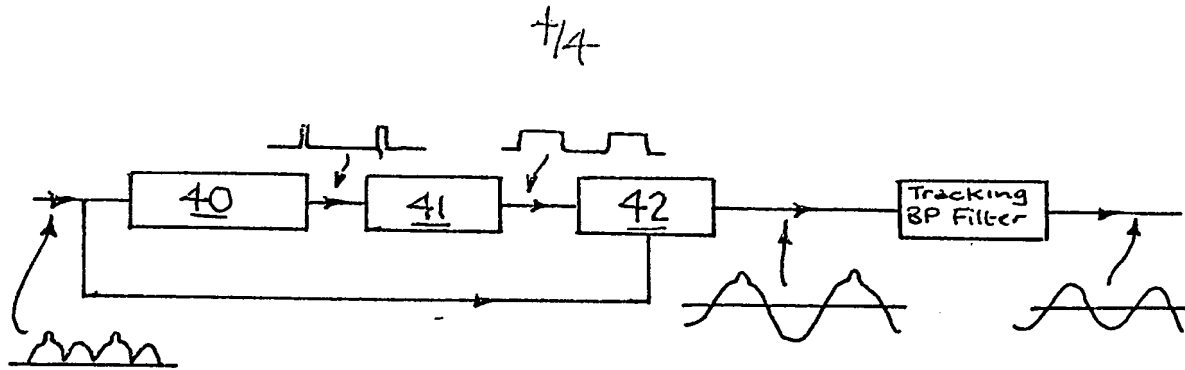
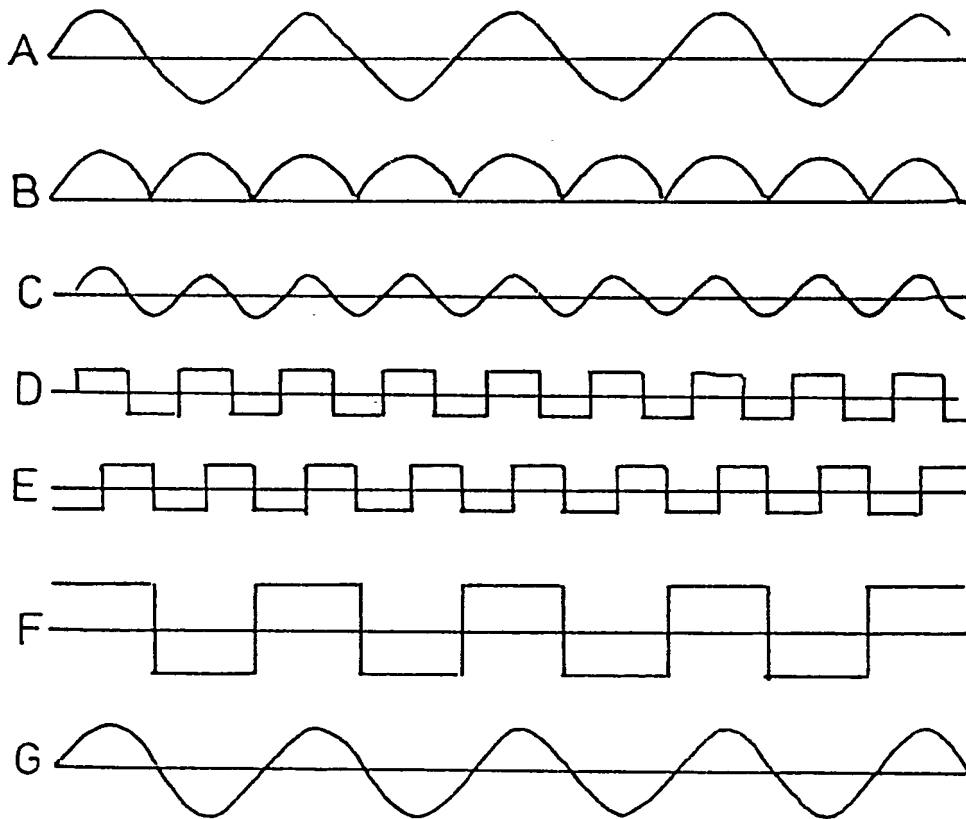


FIG. 6

FIG. 7FIG. 8

SPECIFICATION

Improvements in döppler effect measurements

5 This invention relates to a method of, and apparatus for, making improved Döppler effect measurements, for example to measure the velocity of different regions of a surface subjected to vibration.

10 It is known that a three dimensional picture of the vibration velocity of a vibrating surface can be built up by splitting laser light into two beams, one of which has its frequency shifted by a constant amount in a frequency-shifting mechanism and the other of which is reflected normally from the vibrating surface. The two beams are recombined and fed to a photon-sensitive detector (e.g. a photocell) where
15 beats are generated. These beats consist firstly of a steady beat at a frequency corresponding to the constant frequency shift introduced by the frequency-shifting mechanism and secondly of a varying beat caused by the motion of the specific point on the vibrating surface from which the other of the two split beams was reflected. If this point on the surface is moving towards the detector, the beat frequency is increased above the steady beat frequency and conversely, it is decreased, if
20 the specific point is moving away from the detector.

By choosing the steady beat at a convenient value (e.g. 10.7 or 6.17 MHz) it is possible to
25 use readily obtainable electronic equipment to process the electrical output from the detector and since the phase information of the beats imposed on the detector output is preserved throughout a measurement, there are no problems in displaying the changes in the beat frequencies as a function of time as the laser light is scanned across the vibrating surface, thus producing a series of velocity/time curves which give the required three-dimensional picture.

30 The steady frequency shift can be produced in a variety of different mechanisms such as a frequency shifting disc, a Pockles cell or a Bragg cell but these components are expensive and/or troublesome in use. This invention seeks to eliminate the need for such a frequencyshifting mechanism.

According to one aspect of the invention there is provided a method of determining the
35 Döppler shift occurring in a beam of radiation reflected from a vibrating surface having a component of motion in the travel direction of the said beam, which method comprises deflecting part of a composite beam of radiation away from the said beam to form a part beam, reflecting said part beam from a surface having no component of motion in the travel direction of the part beam and recombining the beam and part beam after their respective reflections to form a new composite
40 beam of radiation on which a beat frequency is imposed, impinging the new beam onto a radiation electrical signal transducer to obtain therefrom a full wave rectified electrical signal related to the beat frequency imposed on the new composite beam, operating on the full wave rectified signal with means capable of distinguishing those half cycles of the full wave rectified signal resulting from movement of the surface away from the detector from the other half cycles resulting from movement of the surface towards the detector, and switching means for drectifying the full wave rectified signal, which switching means is sensitive to the respective polarity of the said those half cycles or the said other half cycles.

70 The distinguishing means can operate on the basis of a naturally-occurring difference between the said those and the said other half cycles, but if a sufficiently obvious naturally-occurring difference is not available, it can be artificially generated (e.g. by imposing a characterising waveform selectively to the said those or to the said other half cycles).
75 Suitably, the creation of the drectified waveform is effected using switching means, synchronised with a vibration frequency of the surface, to change the polarity of every alternate half wave (or lobe) of the full wave rectified signal. Where the vibrations are generated from an electrical drive signal, the required synchronising signals for the switching means can be extracted from the said drive signal.

Conveniently, the output signal from the detector is single sideband modulated on a suitable carrier frequency (e.g. 10.7 MHz) and double, double phased modulation principles can be employed with advantage to operate on the output signal from the detector.
85 A further aspect of the invention relates to an improved Döppler effect measurement apparatus adapted to perform the method set out above in the method statement of the invention.

The invention will now be further described, by way of example, with reference to the accompanying drawings in which:
90 Figure 1 shows a prior art velocimeter set up and Figure 2 the electrical output therefrom,
95 Figure 3 shows velocimeter apparatus in accordance with the invention,
100 Figure 4 shows the output from the apparatus of Figure 3,

105 Figure 5 shows equipment for labelling the true positive lobes of the output of Figure 4,
110 Figure 6 shows a sequence of waveforms generated in equipment (such as that shown in Figure 5) but for labelling the true negative lobes of the output of Figure 4,

115 Figure 7 shows equipment to effect a drectification of the output of Figure 4 following the labelling, and
120 Figure 8 shows a sequence of waveforms generated in the equipment of Figure 7.

125 Figure 9 shows a sequence of waveforms generated in the equipment of Figure 7.

130 Figure 10 shows a sequence of waveforms generated in the equipment of Figure 7.

Figure 11 shows a sequence of waveforms generated in the equipment of Figure 7.

Figure 12 shows a sequence of waveforms generated in the equipment of Figure 7.

The invention will now be further described by way of example with reference to Figures 1 and 2.

Figure 1 shows the known equipment in which a beam 10 of laser light (e.g. Helium/-Neon laser light) is generated in a laser emitter 11 and split into two part beams 10a, 10b by a half-silvered reflector 12. The part beam 10a is reflected off a retroreflective disc 13 rotating at a constant speed. The reflection from a disc part which is constantly moving towards or away from the reflector 12 introduces a steady frequency shift in the part beam 10a returning from the disc 13. The other part beam 10b is fed to the surface whose velocity is to be mapped (here shown as the cone 14 of a loudspeaker) via a pair of mirrors 15, which are controlled to produce a sweep of the laser light spot, created by part beam 10b, across the cone 14. Unless the spot illuminated on the cone 14 is stationary relative to the transit direction of the beam 10b a further frequency shift will be imposed on the beam 10b reflected from the cone 14. In the half-silvered mirror 12, the returning beams 10a and 10b are recombined to form a new composite beam 10c which impinges on a photocell 16. The rotational speed of the disc 13 is adjusted to give a steady beat frequency of 10.7 MHz on the returning part beam 10a and the cone 14 introduces a varying beat frequency of up to several tens of KHz on the returning part beam 10b. Thus the output of the photocell 16 is $10.7 \text{ MHz} \pm 0$ to (say) 100 KHz and this is processed in a radio frequency amplifier 17, an FM tuner 18 and a phase-sensitive detector 19. The envelope signal 20 from the detector 19 is fed to a computer 21 (e.g. a BBC micro). To drive the cone 14, an audio signal 22 is generated in a VCO 23 and power amplifier 24, the VCO 23 being driven by a D/A converter 25 receiving a digital signal 26 from the computer 21. A further audio output signal 27 is taken from the VCO 23 and fed to a phase and waveform switching unit 28 driven by a further digital signal 29 from the computer 21 and the unit 28 feeds an audio signal 30 to the detector 19. The output signal 18a from the tuner 18 will be a sine wave as shown in Figure 2 where the abscissa is time t and the ordinate is a measure of the velocity of the spot on the cone 14 being scanned at the time t . The output envelope signal 20 fed to the computer 21 will be a DC level which rises and falls with the amplitude and phase of the sinewave signal 18a. It will be positive for "in phase" signals, negative for "out of phase" signals and zero for "90°" and "270°" signals. To display the signal 20, a digital output 31 can be taken from the computer 21 and fed to a printer/plotter 32 and/or a raster signal 33 can be fed to a VDU 34 to produce a 3D display of the velocity pattern created on the

cone 14 by the audio signal 22.

To obtain a sweep of the spot over the cone 14 a digital signal 35 can be extracted from the computer 21 fed to the mirrors 15.

The equipment shown in Figure 1 is prior art and is described for example in Bank and Hathaway's paper (1658 B-7) presented to the Audio Eng. Soc. Proc. 66 Convention 1980.

Figure 3 shows one embodiment of velocimeter according to the invention and the main features of difference are the elimination of the frequency shifting mechanism (provided by the disc 13 in Figure 1) and the incorporation of further electronic processing to handle an infinite bandwidth signal which results when there is no steady beat frequency on the recombined beam 10c. Where equivalent units are employed in both the Figures 1 and 3 equipment the same reference numerals have been used in both Figures and the following analysis will concentrate on the additional/modified components.

In place of the rotating disc 13 a stationary mirror 13' is used in the Figure 3 embodiment so that the output from the photocell 16 is a signal having a beat frequency which can vary from zero Hz to (say) 150 KHz. Unfortunately the "negative" beat frequencies "wrap around" zero Hz and also appear as "positive" frequencies. Thus, if the output were fed via an amplifier directly to the phase sensitive detector 19 the audio output 20 would be a full-wave rectified output with every other half cycle (or lobe) folded around zero volts (as shown in Figure 4). To cope with this, the equipment of Figure 3 includes a negative lobe reinstatement unit 35 which receives the full-wave rectified audio output 18a from the FM tuner 18 and performing synchronised switching from a switching signal derivation unit 36 generates a true sinusoidal audio waveform 35a from the output 18a.

The switching unit 36 operates as shown in Figures 7 and 8. Figure 8 shows at A the input signal on the recombined beam 10c. At B is shown the transduced output signal from the photocell 16. A switching waveform (shown at F in Figure 8) is derived from signal 8B by extracting the first harmonic (shown at 8C) and squaring this to produce the waveform shown at 8D. This is then fed to a phase-locked loop to produce another waveform (shown at 8E) 90° out of phase with waveform 8D. By dividing 8E by two, one obtains the waveform shown at 8F which can be used (on line 36a in Figure 3) to switch the unit 35 and reconstitute a true sinusoidal waveform (shown at 8G) from the full-wave rectified signal shown at 8B. However, if ever the signal should disappear or be attenuated below the operating threshold of the processing circuit, the electronics described will lose synchronisation and on reappearance the signal could reappear 180° out of phase so that phase continuity will be lost.

We have discovered, however that this apparent hurdle to the use of the simple optical system of Figure 3, can be easily avoided since in many vibrating systems there is some asymmetrical distortion of the output waveform 8B so that in practice one set of lobes (e.g. the positive) will be slightly larger than the other set of lobes enabling a simple threshold circuit to distinguish which of the adjacent lobes in the full-wave rectified output derives from a positive input lobe and which a negative. Thus all that may be necessary to determine the true phase is to arrange that the circuit triggers on the larger of the two rectified lobes and to use a signal derived from this to do the switching. When this facility is provided, the circuit will start up in the correct phase every time ensuring correct phase relationship in the reconstituted signal of 8G.

Figure 7 shows the units required to achieve this correct phase sine wave reconstruction. The signal of 8B is fed to a comparator 40 then to a phase-locked loop 41 and finally to a +1, -1 switching amplifier 42.

Where there is doubt that the positive and negative lobes of the input signal will be sufficiently obviously distinguishable, it is possible to employ a further feature of this invention and to "tag" one of the two lobes to artificially increase its amplitude.

How this can be done is shown in Figures 5 and 6.

The signal from the VCO 23 (shown at A in Figure 6) is subjected to lobe labelling in a unit 37 shown in Figure 3. The unit 37 comprises a squarer 37a (see Figure 5) which outputs the waveform shown at B in Figure 6. This is shifted 90° in phase in a phase lock loop and 90° phase shifter 37b to produce the waveform shown at C in Figure 6. Short duration pulses (shown at 6D) are produced in a negative going zero-crossing detector 37c and pulse producer 37d in Figure 5 and by adding the waveforms 6A and 6D in an adder 37e, the tagged lobe waveform shown at E in Figure 6 is produced.

Clearly other mechanisms for "tagging" alternate lobes are possible and the arrangement described should be understood to be one such. What is required is a system for allowing phase continuity to be preserved on start up or should synchronisation be lost.

It now only remains to transduce the frequency variation of from 0 Hz to 150 KHz (called the "baseband" signal) on waveform 8B into a voltage which varies from 0 volt to some maximum value (say 10 volts) and thus transduce the rectified waveform of Figure 4 exactly. The problem is the vast range of input frequencies needing transduction at up to 20 KHz rate.

The novel idea is to single sideband modulate this baseband frequency range onto a 10.7 MHz carrier and to use a standard FM IF strip with all its built in signal conditioning

facilities to transduce the signal.

This is best carried out by a double, double phased modulation principle using the units 17b to 17e in Figure 3. Firstly the baseband is modulated twice onto a subcarrier at 150 KHz in unit 17b, once, with the subcarrier phase at 0 degrees and also simultaneously with the subcarrier phase at 90 degrees (i.e. in quadrature). The two sets of lower sidebands resulting from this process are then filtered out in unit 17c and used to modulate a 10.7 MHz carrier simultaneously at both 0 degrees and 90 degrees in unit 17d. If the results of these two modulations are added together in unit 17e, one of the two sidebands around 10.7 MHz will cancel out leaving the baseband frequencies translated up to 10.7 MHz. If two quadrature oscillators are used, the end result is a frequency translation from (0 Hz to 150 KHz) up to 10.7 MHz plus that range. This may then be fed into an FM IF strip in the FM tuner 18 for demodulation to the desired rectified sine wave signal 18a.

Although this specification has referred to light as the radiation employed in the method of the invention it is important to realise that it is not essential the radiation be light or indeed electromagnetic. What is required is that the object whose vibration is being monitored via a Doppler shift is large compared to the wavelength of the radiation, that a transducer is available to produce electrical signals related in some known way to the Doppler shift generated and that the coherence length of the radiation is comparable with available engineering tolerances in the setting up of the two part beams. Ultrasound can be used in place of light and X-rays or radar waves can be used in place of laser light.

CONCLUSION

The net result of the electronics shown in Figure 3 is:

(1) A laser beam frequency shifting mechanism 13 is no longer required—with all its attendant noise, cost and drive problems.

(2) The optical system will be simplified as it will not have to accommodate any frequency shifting mechanism at all. A simple mirror 13' (or retroreflective surface or even a simple scattering surface) is all that is required.

(3) "Front end" electronics will be rendered easier to produce and more satisfactory in practice—as the maximum frequency required from the photocell and its amplifier is only about 150 KHz instead of 5 to 10 MHz.

(4) In some cases the technique may require the system to "predistort" the signal to the test object in order to mark one or other of the lobes of the sine wave excitation frequency.

CLAIMS

1. A method of determining the Doppler

shift occurring in a beam of radiation reflected from a vibrating surface having a component of motion in the travel direction of the said beam, which method comprises deflecting part of a composite beam of radiation away from the said beam to form a part beam, reflecting said part beam from a surface having no component of motion in the travel direction of the part beam and recombining the beam and part beam after their respective reflections to form a new composite beam of radiation on which a beat frequency is imposed, impinging the new beam onto a radiation electrical signal transducer to obtain therefrom a full wave rectified electrical signal related to the beat frequency imposed on the new composite beam, operating on the full wave rectified signal with means capable of distinguishing those half cycles of the full wave rectified signal resulting from movement of the surface away from the detector from the other half cycles resulting from movement of the surface towards the detector, and switching means for derectifying the full wave rectified signal, which switching means is sensitive to the respective polarity of the said those half cycles or the said other half cycles.

2. A method as claimed in claim 1, in which the distinguishing means operates on the basis of a naturally-occurring difference between the said those and the said other half cycles.

3. A method as claimed in claim 1, in which a difference between the said those and the said other half cycles is artificially generated.

4. A method as claimed in claim 3, in which a characterising waveform is selectively added to the said those or to the said other half cycles.

5. A method as claimed in any preceding claim, in which the creation of the derectified waveform is effected using switching means, synchronised with a vibration frequency of the surface, to change the polarity of every alternate half wave of the full wave rectified signal.

6. A method as claimed in claim 5, in which the required synchronising signals for the switching means are extracted from an electrical drive signal used to generate the vibrations.

7. A method as claimed in any preceding claim, in which the output signal from the detector is single sideband modulated on a suitable carrier frequency.

8. A method as claimed in claim 7, in which the output signal from the detector is operated on using double, double phased modulation principles.

9. A method as claimed in any preceding claim, in which the beam of radiation is a beam of laser light.

10. A method for measuring the velocity of different regions of a surface subjected to vibration substantially as hereinbefore described with reference to Figures 3 and 4 of the ac-

companying drawings, or Figures 3 and 4 as modified by Figures 5 and 6, by Figures 7 and 8 or by Figures 5 to 8.

11. Apparatus for determining the Doppler shift occurring in a beam of radiation reflected from a vibrating surface having a component of motion in the travel direction of the said beam, which apparatus comprises means for deflecting part of a composite beam of radiation away from the said beam to form a part beam, means to reflect said part beam from a surface having no component of motion in the travel direction of the part beam and means to recombine the beam and part beam after their respective reflections to form a new composite beam of radiation on which a beat frequency is imposed, a radiation electrical signal transducer, means to impinge the new beam onto the transducer to obtain therefrom a full wave rectified electrical signal related to the beat frequency imposed on the new composite beam, means to operate on the full wave rectified signal to permit those half cycles of the full wave rectified signal resulting from movement of the surface away from the detector to be distinguished from the other half cycles resulting from movement of the surface towards the detector, and switching means for derectifying the full wave rectified signal, which switching means is sensitive to the respective polarity of the said those half cycles or the said other half cycles.

12. Apparatus as claimed in claim 11, in which the beam of radiation is obtained from a laser light emitter.

13. Apparatus as claimed in claim 11 or claim 12, in which means is provided to artificially "tag" either the said those half cycles or the said other half cycles.

14. Apparatus as claimed in any one of claims 11 to 13, in which the switching means is synchronised to an electrical drive signal used to generate the vibrations.

15. Apparatus as claimed in any one of claims 11 to 14, in which the vibrating surface is part of a loudspeaker.

16. Apparatus for measuring the velocity of different regions of a surface subjected to vibration substantially as hereinbefore described with reference to, and as illustrated in Figure 3 of the accompanying drawings, Figure 3 as modified by Figure 5, Figure 3 as modified by Figure 7, or Figure 3 as modified by Figures 5 and 7.

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